MACHOs and the clouds of uncertainty

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I review proposals for explaining the current gravitational microlensing results from the EROS and MACHO surveys towards the Magellanic Clouds. Solutions involving massive compact halo objects (MACHOs), both baryonic and non-baryonic, as well as solutions that do not require MACHOs, are discussed. Whilst the existence and nature of MACHOs remains to be established, the prospects for achieving this over the next few years are good.

1 Microlensing and MACHOs — where we now stand

1.1 The EROS *and* MACHO *surveys*

EROS and MACHO [1], have been monitoring millions of stars in the Large and Small Magellanic Clouds (LMC and SMC) on an almost nightly basis since 1992, enabling them to search for MACHOs with masses from around $10^{-4}\ M_\odot$ up to several Solar masses. EROS also undertook a survey of a smaller number of LMC stars with a sampling of 30 mins, extending its sensitivity down to $10^{-8}\ M_\odot$. Other experiments are now also targeting the Magellanic Clouds but have yet to publish full results, so in this review we shall concentrate on the EROS and MACHO surveys. Details of these and the other surveys, and of the principles of microlensing, are described elsewhere in these proceedings.

The MACHO experiment has published around fifteen candidates towards the LMC and two candidates towards the SMC. One of the LMC candidates, MACHO LMC-9 [2], appears to be a caustic-crossing event due to a binary lens, as is the SMC candidate, 98-SMC-1 [3]. EROS has three candidate events towards the LMC and two towards the SMC (including 98-SMC-1). Of the two targets, the LMC has been the monitored the most intensively. It is worth noting that there are three strong arguments against the candidate microlensing events being instead some hitherto unknown population of variable stars. Firstly, the impact parameter distributions are consistent with microlensing expectation. Secondly, the positions of the source stars on the

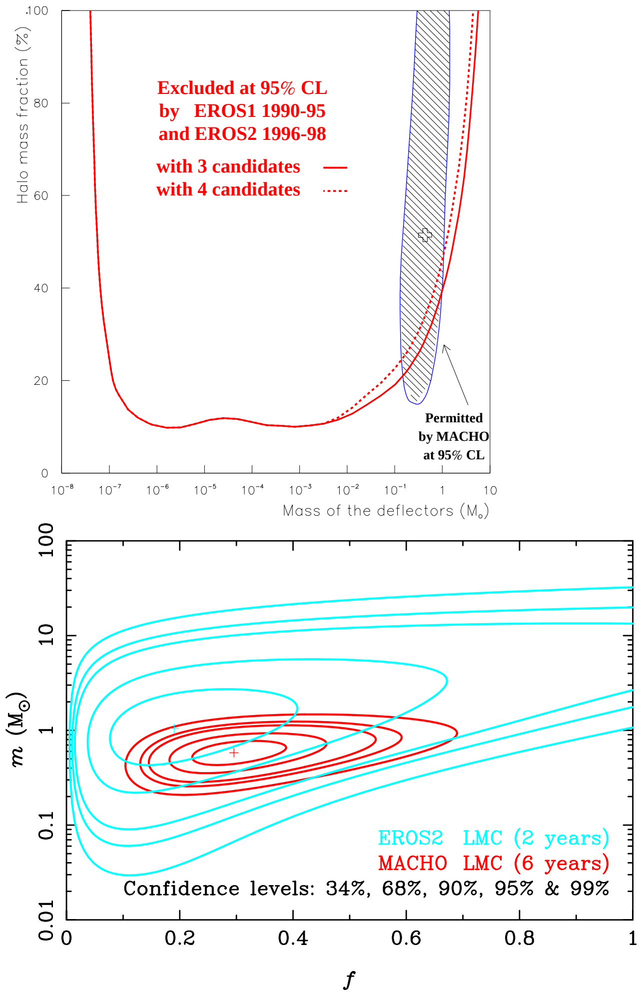

Figure 1: *Left panel*: Upper limits on the halo fraction from the Eros1+2 LMC and SMC experiments, with the Macho two-year LMC results shown by the shaded region (figure courtesy of Eros). *Right panel*: Likelihood analysis of the MACHO fraction f and mass m from the Eros2 two-year and Macho six-year LMC datasets, assuming the detected events are due to MACHOs. Both figures are for a "standard" isothermal dark halo.

HR diagram show no obvious clustering. Thirdly, in the case of the microlensing experiments looking towards the Galactic Bulge, the optical depth deduced only from clump giant sources is consistent with that inferred from all the events implying that, at least along this line of sight, contamination levels are small.

1.2 What we've learned so far

Before discussing the different interpretations of the microlensing results we should first reflect upon several conclusions which we are led to from both the Eros and Macho datasets, and which have important implications for our understanding of Galactic dark matter. They underscore the considerable success of microlensing so far.

It is important to emphasize that the Macho and Eros LMC/SMC results are statistically consistent with one another, as can be seen in Figure 1. The absence of short-duration events in either survey limits the contribution of low-mass MACHOs [4]. The Eros1+2 LMC and SMC limits in Figure 1 indicate that $f < 0.12$ for MACHOs in the mass range $10^{-6} - 10^{-2}\ M_\odot$. Both Eros and Macho exclude brown dwarfs as a major constituent of the dark matter and both also agree that MACHOs of around a Solar mass or below do not dominate the halo dark matter

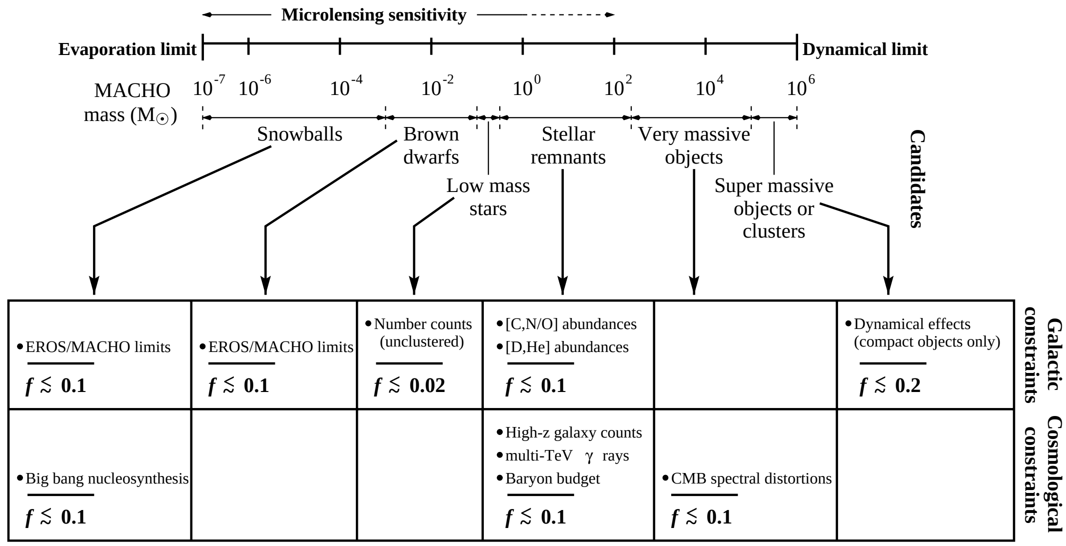

Figure 2: Baryonic MACHO candidates and constraints

budget. If one chooses to interpret the detected events as being due to MACHOs, both EROS and MACHO LMC datasets prefer a MACHO fraction $f \sim 0.2 - 0.3$ and mass $m \sim 0.5 - 1\ M_\odot$. However, the teams themselves have interpreted their results in contrasting fashion, with EROS choosing to place only upper limits on f (as shown in the left panel in Figure 1) and MACHO arguing that its dataset indicates a positive detection of MACHOs (as shown in the right-hand panel). The uncertainty is not whether microlensing has truly been observed, but whether it being caused by MACHOs.

2 MACHO solutions

2.1 Dependency of MACHO mass on halo model

Analyses of the MACHO mass inferred from microlensing data always assume some underlying model for the distribution function of the Galactic halo. The structure of the Galactic halo is very uncertain, so one might expect a large systematic error in MACHO mass determinations. Various studies employing a range of flattened halo models and anisotropic velocity distributions show that the MACHO mass determination is actually rather robust. In particular, brown dwarfs appear to be irreconcilable with current datasets [5]. If the microlensing events are due to MACHOs then their mass is of the order of a Solar mass.

2.2 Baryonic MACHOs

Figure 2 shows the range of baryonic MACHO candidates, as well as a summary of present constraints on them [6]. The microlensing mass sensitivity currently spans about seven of the thirteen orders of magnitude of the candidates, and provides the strongest constraints on snowballs and brown dwarfs. Other constraints involve a wide range of astrophysical arguments but can be loosely classified into those derived from properties of our Galaxy and those derived from cosmological considerations. In order to translate the latter into limits on the halo fraction f for our own Galaxy, one must assume it to be cosmologically representative, which may or may not be the case.

It is interesting to note that the combination of Galactic and cosmological constraints now limits the abundance of all the baryonic MACHO candidates to well below that required to explain the halo dark matter. In fact, even if we populate the halo with a mixture of baryonic candidates, they can provide only just over half of the dark matter if they are to remain consistent with all constraints. However, low-mass stars are the only candidates to be excluded by direct observation. The candidate which is most compatible with the microlensing mass scale is the white dwarf. Ibata et al. have detected a number of faint moving objects in the Hubble Deep Field (HDF) consistent with a population of white dwarfs contributing a significant fraction of the halo dark matter [7]. Subsequently, Ibata et al. obtained spectroscopy of two nearby high proper motion white dwarfs, inferring these to be possibly the nearby counterparts of the HDF objects. The observations clearly lend support to the microlensing results.

These positive findings contrast with the range of constraints in Figure 2. Remnants are constrained by both Galactic and cosmological arguments, which all indicate $f \lesssim 0.1$, barely allowing consistency with the microlensing results [8]. Galactic limits relate to the production of helium and metals, and the depletion of deuterium by the precursor stars. Cosmological limits come from the lack of precursor starlight at high-redshift, the observation that the Universe appears to be optically thin to TeV γ rays out to the redshift of blazar Mkn 501 at $z = 0.034$ (hence the infrared background indicative of the precursor stars is low or not present), and from the fact that too much of the "baryon budget" allowed by Big-Bang nucleosynthesis predictions may still be in gas by $z \sim 1$. All of these arguments can be countered on an individual basis. For example, the recent positive detection of an infrared background [9] casts doubt on our understanding of the intrinsic spectrum of Mkn 501, whilst the latest cosmic microwave background data from BOOMERANG favour a baryon density 50% larger than nucleosynthesis models predict [10]. However, the fact that these diverse constraints are all consistent with each other seriously undermines the white-dwarf hypothesis.

A recently proposed alternative to the white-dwarf solution is the beige dwarf, a kind of "genetically-modified" brown dwarf. Hansen [11] has shown that slow accretion of gas onto a brown dwarf can prevent the core temperature from rising to the point where hydrogen-burning commences. Beige dwarfs can have masses up to 0.3 $M_\odot$ if they continue to accrete at the maximum rate over a Hubble time, so providing compatibility with microlensing data.

2.3 Non-baryonic MACHOs

Though MACHOs are generally assumed to be baryonic there are a few non-baryonic cold dark matter (CDM) candidates, such as primordial black holes (PBHs), which would give rise to microlensing signatures. The fact that microlensing searches now exclude more than half of the dark matter from comprising MACHOs may be both good news and bad for CDM. On the one hand it supports the view that at least half of the dark matter is non-baryonic (though, conceivably, it could also comprise cold clumps of gas). On the other hand it limits the contribution of non-baryonic MACHO candidates as much as it does baryonic dark matter. Furthermore, if the detected microlensing events are, at least in part, due to MACHOs then we need either a combination of baryonic dark matter and CDM or *two* types of CDM: one to provide the MACHOs and one to provide the rest of the dark matter. This constitutes at least an aesthetic constraint: if MACHOs are being detected it may be easier to believe they are baryonic than to believe in two species of CDM.

The PBH scenario also requires fine-tuning. A first-order phase transition at the QCD epoch provides a natural formation mechanism to produce PBHs of about the right mass [12], however the PBH abundance must be finely tuned in order that they do not rapidly dominate the energy density of the early Universe as it expands.

3 Non-MACHO solutions

Do the microlensing results require MACHOs at all? We now examine the arguments for and against a number of alternative solutions.

3.1 Milky Way disk

The microlensing contribution of a standard Milky Way disk is an order of magnitude too small to account for the LMC events. Evans et al. [13] investigated the possibility that the disk may be significantly flared and warped in the direction of the Magellanic Clouds. Whilst such a model could account for the events, a subsequent study ruled out this proposal on the basis of star counts [13]. Gates & Gyuk [14] have advocated the existence of an old, super-thick disk with a scale height of ~ 3 kpc comprising white-dwarf remnants. The model succeeds in evading the constraints on white dwarfs because their total mass is much less than required by halo models. Whilst the model is strictly a very fat disk, it can also be viewed as a strongly dissipated MACHO halo. It is an *ad hoc* solution but, more importantly, a currently viable one.

3.2 Intervening debris

Zhao [15] has considered the effects of stellar "debris" along the line of sight to the Magellanic Clouds, either associated in some way with the Clouds or simply a chance alignment of some disrupted satellite galaxy. The proposal received tentative observational support from Zaritsky & Lin [16], who interpreted an observed vertical HR extension to the LMC red clump population as evidence of a foreground stellar population. Beaulieu & Sackett [17] claimed that such a feature is indicative of stellar evolution rather than a foreground population, whilst Bennett argued that if the structure has a similar star formation history to the LMC its optical depth would be an order of magnitude too small to explain the MACHO results [17]. Gould [18] has presented a series of arguments against intervening populations. If they are unassociated with the Magellanic Clouds then they must have a highly improbable spatial and velocity alignment with the Clouds to have remained undetected. On the other hand, if the debris is associated with the Clouds, Gould argues that its mass function would need to be dominated by sub-stellar objects in order to explain the microlensing timescales. However, it has been suggested recently that such a population may have been observed [19]. Of course, it is possible that the debris is mostly dark, in which case it is essentially a MACHO solution in disguise.

3.3 LMC/SMC self-lensing

The last possibility is that the sources in the Magellanic Clouds themselves are also providing the lenses [20]. Gould [21] has shown that if the LMC can be represented by a thin disk in virial equilibrium then its optical depth would be about an order of magnitude too small to explain the microlensing results. Though this may be too strict an assumption for what is a poorly understood structure, recent self-consistent numerical models yield similar optical depths [22].

The strongest support for the self-lensing scenario may come from the microlensing data. The two binary caustic crossing events, MACHO LMC-9 and 98-SMC-1, provide information on their line-of-sight location. Their caustic-crossing timescales indicate the time taken for the caustic to cross the face of the source and so depends on the size of the star and the projected transverse velocity of the lens. The typical transverse velocity of halo or Galactic disk lenses is of the order of 1000 km s^{-1} or more, where as for lenses in the Clouds it is typically only $\sim 60 - 80$ km s^{-1}. In the case of 98-SMC-1, the second caustic crossing is well resolved [3] and the projected velocity is determined to be 65–75 km s^{-1}, consistent with it being within the SMC and highly inconsistent with it being a MACHO. The second caustic crossing of MACHO LMC-9 is only partially resolved [2] and the projected velocity is inferred to be only 20 km s^{-1}, which is low even for a lens within the LMC, but certainly excludes a MACHO interpretation. Statistically, the two binary events strongly favour self-lensing over Galactic MACHOs [23]. However, it is possible that the A-type source of event LMC-9 may itself be an equal luminosity binary [2], in which case the timescale is indicative of the binary separation and the projected transverse velocity could be large enough to be consistent with the lens being a MACHO after all.

Finally, the lenses could reside in a dark halo associated with the Clouds, rather than the Milky Way halo [23]. Alves & Nelson [22] have recently argued that the LMC rotation curve does not require a halo, though in any case an LMC halo must count as a MACHO solution.

4 Summary and future prospects

Despite the many successes of microlensing, as yet there is no firm evidence that we are detecting MACHOs. Of the proposed solutions involving MACHOs, halo white dwarfs appear to be all but excluded by a host of constraints, whilst beige dwarfs and primordial black holes, though not constrained, require finely-tuned formation scenarios. As far as non-MACHO solutions are concerned, visible stellar populations do not appear to be able to provide the observed optical depth. Viable models include a dark super-thick disk, mostly dark tidal debris, or dark haloes around the Magellanic Clouds. Each of these solutions requires a major revision in our understanding of the structure of our Galaxy or its satellites, and each is really a MACHO solution in a new form.

In order to resolve the issue what is required is the ability to identify MACHO events from other microlensing events. The Andromeda galaxy presents an attractive possibility. If it is surrounded by a spherical halo of MACHOs the microlensing rate to the far side of its inclined disk should be larger than the rate towards the near side. The detection of such a gradient would provide clear evidence of MACHO rather than stellar lensing. Experiments are now in progress to try to detect this signal [24]. For our own Galaxy, the spatial distribution of the LMC microlensing events, or the velocity or magnitude distributions of the sources [25], may soon provide a conclusive answer. If not, measurements by astrometric satellites such as SIM [26] or GAIA could settle the issue by determining the line-of-sight location of a handful of events.

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